SURFACE ABUNDANCES OF LIGHT ELEMENTS AS DIAGNOSTICS OF TRANSPORT PROCESSES IN THE SUN AND SOLAR-TYPE STARS.

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ABSTRACT. Observations of the surface abundances of lithium, beryllium and helium-3 in the Sun and in solar-type stars of different ages should be interpreted in a coherent way. The abundance of lithium at the surface of a star decreases slowly with age; for stars of the same age it decreases with mass and a dependence on the rotation velocity is suggested. The solar surface lithium is depleted by a factor of 100 relative to the cosmic abundance while an He-3 enrichment of 15% at the solar surface during evolution is suggested.

Observations favour the hypothesis of a slow transport process at work between the outer convective zone and the radiative interior of these stars. Orders of magnitude of the transport coefficient as well as its dependence upon the physical parameters can be inferred from surface abundances of light elements, but at the moment we are far from producing a completely consistent modelization.

1. Introduction

Up to now, there are very few observable quantities which can provide us information on transport processes at work inside the stars. Data on the internal rotation rate of the Sun are now available owing to helioseismological measurements, but for other stars the observations only provide the surface rotation velocity and the surface abundances.

The abundances of the light elements observed at the surface of the Sun and solar-like stars are the best tool to understand the processes of mixing acting in the interior of those stars. Although we have more information for the Sun, any theory of the solar mixing should consist in the proper application to the Sun of physical models applicable to other stars.

The observed abundances of the light elements ^{7}Li, ^{9}Be, ^{10}B and ^{11}B are always very small; moreover these elements do not contribute to the energy generation rate in stars so that they can be considered as passive contaminants. The case of ^{3}He is a little different since it enters the network of hydrogen burning reactions. The distribution of ^{7}Li, ^{9}Be and ^{3}He obtained, at solar age, in the standard solar model of Lebreton and Maeder (1986) are given in fig. 1. ^{7}Li, ^{9}Be, ^{10}B and ^{11}B only survive in those outer regions of the star where the temperature is low enough to prevent them from being destroyed by nuclear reactions. According to the updated cross-sections of nuclear reactions of Caughlan and Fowler (1988), ^{7}Li burns at temperatures of about 2.7 10^{6} °K, ^{9}Be is destroyed at about 3.5 10^{6} °K and ^{10}B and ^{11}B around 5.0 10^{6} °K; thus in solar-like stars all these elements are confined to a narrow region extending a few pressure scale heights below the convective zone. The sharp decrease with depth of the Li and Be abundances which can be seen in fig. 1 is due to the strong dependence of their destruction rates with temperature (the rate of the ^{7}Li(p,α)^{4}He reaction is proportional to about T^{30} around 2.5 10^{6} °K). The peaked distribution of ^{3}He results from the balance between destruction and creation in intermediate regions of the Sun while ^{3}He is not affected by nuclear reactions in outer regions.

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The interpretation of the surface abundances of the light elements relies on the physical processes at work in the outer layers of stars and, of course, on the structure of those layers which varies for stars of different masses. Thus we shall only consider here the case of solar-analogues with masses between $0.8M_\odot$ and $1.2M_\odot$ (i.e., 5000 °K$\leq T_{eff} \leq$6200 °K) and are still in the main-sequence stage. In these young population I stars the lithium abundance has been extensively studied but very little information can be obtained from the other species. After a short review of the observational results we shall discuss the existing modelizations, their difficulties and their successes.

2. Observations of surface abundances.

2.1. LITHIUM, BERYLLIUM, BORON

Let us first review the tools available to determine the surface abundances. Since for the light elements, the abundances to be measured are very small (Li/H $\approx 10^{-9}$ in number), only the resonance lines can be used (see for instance TableII in Boesgaard (1976)), which lists the resonance lines of the light elements either neutral or singly ionized. The only lines lying in the visible spectrum are the Li I and marginally the Be II lines. The boron lines are all in the UV spectrum. The ionization potential of Li I is very low and thus lithium is in the form of Li II at about 5800 °K in the photosphere of solar-like stars. The lithium line at 6707 Å is blended by an iron line. Most Be is in the form of Be II in solar type stars, but the UV spectrum is crowded in the ionization region and the stronger line at 3130.4 Å is badly blended. Thus most of the observational data concern lithium abundances while very little is known about beryllium and almost nothing about boron. Moreover the abundance determinations are possible in objects of moderate rotation only.

A lot of work has been done during the last three decades to measure the abundances of the light elements at the surface of stars and to correlate them with stellar parameters. Herbig (1965) was a pioneer in the subject and showed for the first time a clear correlation between stellar age and abundance of lithium in main-sequence stars of spectral type G. Many complementing results have been obtained afterwards by Wallerstein et al. (1965), Kraft and Wilson (1965), Danziger and Conti (1966), Danziger (1967). The observational results were obtained from photographic plates, most of them at the 200 inch Palomar telescope. They all give the ratio [Li/Ca], which means $\log(\mathrm{Li/Ca})-\log(\mathrm{Li/Ca})_\odot$ (in number), comparing the Li line at 6707 Å to a neighbouring calcium line. All these results clearly establish the general trend of decreasing [Li/Ca] versus age with emphasis on the depletion with respect to the cosmic abundance. Moreover, Bodenheimer (1965) noticed a general decrease of lithium with advancing spectral type, or decreasing mass, which was confirmed by the observations of Zappala (1972), in the Hyades and other open clusters.

Recently, spectroscopy with high-signal-to-noise ratio has become possible due to the great quality of the new instrumentation (see IAU Symposium n°132 on "The impact of very high S/N spectroscopy on stellar physics" edited by G. Cayrel and M. Spite, 1987). This progress has considerably changed the observational landscape since it is now possible to detect very low lithium abundances in faint objects and to separate the iron line from the lithium one.

Duncan and Jones (1983) and Cayrel et al. (1984) observed the lithium line in stars of the Hyades cluster and showed the now very popular decrease of the lithium abundance with the effective temperature (for $T_{eff} \leq$ 6000 °K , see fig. 2b). The lithium abundance appears to depend on the age of the observed object so that its determination in stars of the same (and known) age like the Hyades stars is of great interest. During the last five years the closest clusters and groups have been observed by different authors with the same techniques (see fig. 2a-c and references therein). The following important results can be drawn from fig. 2a-c: 1) the abundance of lithium in the observed stars is either cosmic or depleted. The cosmic abundance inferred from measurements in young hot stars is Li/H $\approx 10^{-9}$ (in number) with little evidence of real variation, as reviewed by Boesgaard et al. (1988). The value found in meteorites (Nichiporuk and Moore, 1974) is a factor 2 larger which is generally attributed to chemical separation; 2) in the older clusters, which have an age greater than a few 10^8 years, the depletion of lithium increases with stellar age for a given mass and at fixed age increases with decreasing mass. Moreover the Li-T_{eff} (i.e., mass) relation for a given cluster is quite-well defined and the intrinsic scatter is rather small,

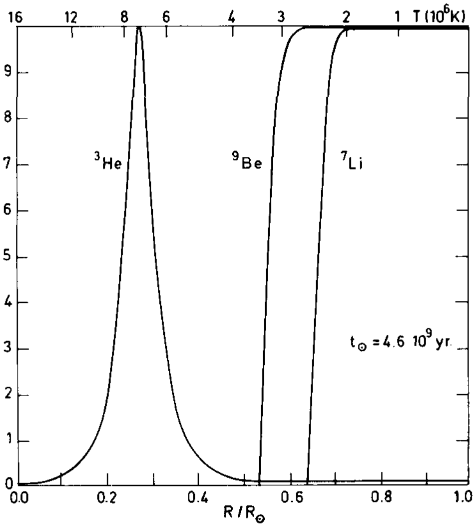

Figure 1 : Abundances of ^{7}Li, ^{9}Be and ^{3}He normalized to their maximum values as a function of the radius and temperature in the standard model of Lebreton and Maeder (1986)

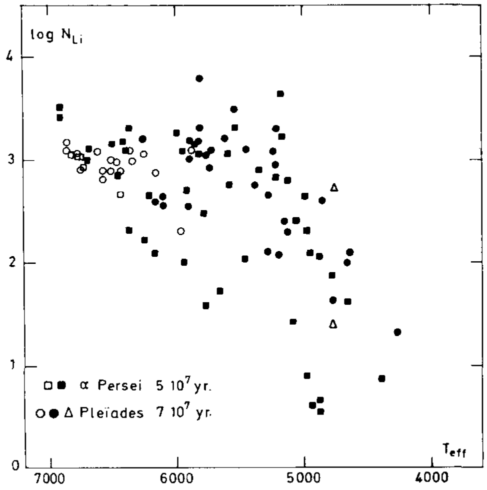

Figure 2a : Observation of the lithium abundance in number of atoms relative to hydrogen, log N_{Li}, in the logarithmic scale where log $N_H = 12$, as a function of T_{eff} in the two young clusters α Persei and the Pleiades. Observations are from Duncan and Jones (1983,•), Butler et al. (1987, Δ), Boesgard et al. (1988b,o) and Balachandran et al. (1988)

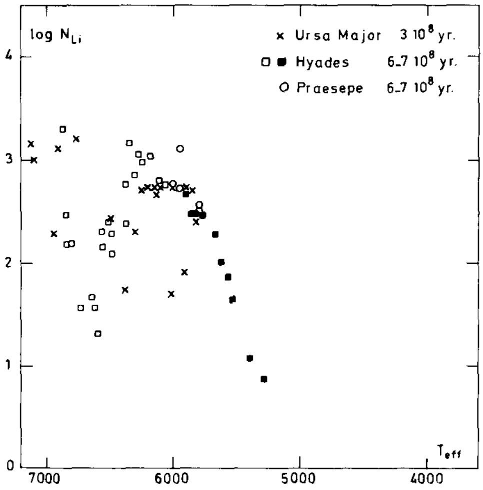

Figure 2b : Same as fig.2a but in the three clusters of intermediate age (Ursa Major, Boesgard et al. (1988a,x) ; the Hyades, Cayrel et al.(1984,), Boesgard and Tripicco (1986a,) and Praesepe, Soderblom and Stauffer (1984,o)).

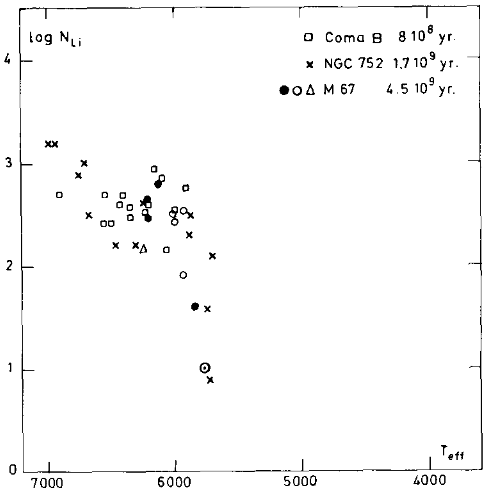

Figure 2c : Same as in fig.2a but in older clusters (Coma Berenices, Boesgard (1987,) ; NGC 752, Hobbs and Pilachowski (1986a,x) and M67, Hobbs and Pilachowski (1986a,•), Spite et al. (1987,o), Garcia Lopez et al. (1988,Δ).

especially in the Hyades. In younger clusters, the dispersion of the Li-abundance at a given T_{eff} may be large but the average depletion is smaller than in the older clusters (see fig. 2a).

Conti (1968) has suggested that rotational braking could be responsible for Li-destruction in stars. Therefore it is worth investigating the possible Li-abundance-rotation and age-rotation relationships in the observed solar-type stars.

In a recent discussion of the available data, Stauffer (1987) points out that while the dispersion among the rotational velocities for a given spectral type is large in the very young cluster α Per, it tends to become less important, as age increases, for clusters of intermediate ages like the Pleiades. At the age of the Hyades, the scatter almost vanishes and the observed relation between rotation and T_{eff} is very well-defined. Moreover, as the age increases, the rapid rotators observed have smaller masses which is probably due to the fact that the time scales of spin down are smaller in higher-mass stars.

Furthermore, recent observations, in α Per and the Pleiades, respectively by Butler et al. (1987) and Balachandran et al. (1988) give some new information on the lithium-rotation relationship. The main result of Balachandran et al. (1988) is that, in the sample observed (46 stars), for a given spectral type all the Li-poor stars are slow rotators while the undepleted stars rotate rapidly. A similar behavior is found in 8 of the 11 Pleiades stars studied by Butler et al. (1987). As discussed by Balachandran et al. (1988), this result could be due either to a process which links the Li-depletion to the rotation rate or to an extended phase of star formation in clusters. Rebolo and Beckman (1988) have found a similar, although more uncertain, trend of "slower rotation less Li" in G stars of similar mass in the Hyades. Whether these results are due to an age spread or to the fact that stars have undergone a different history leading to different initial rotation is still not clear and requires further investigations. It is also worth pointing out that the opposite situation, i.e., fast rotators with no lithium depletion and slow rotators with depletion, at the same spectral type has also been observed in αPer by Butler et al. (1987) and in F and G field stars by Boesgaard and Tripicco (1986,b).

Therefore one has now to be careful when talking about lithium depletion as an age indicator. It is necessary to refer to objects of the same mass or at least same effective temperature and to objects which are rather old (maybe older than the Pleiades).

The Li^6 abundance is very difficult to measure. The Li^6/Li^7 ratio can however be a good indicator as Li^6 is destroyed at much lower temperature than Li^7. Observing several F and G stars Cayrel et al. (1989) have shown that this ratio is always much smaller than the meteoritic value (fig. 3).

2.2. HELIUM-3

The observations of ^{3}He in the solar system are quite difficult to interpret, as reviewed by Lebreton and Maeder (1987). The ^{3}He abundance of the solar atmosphere is extremely difficult to obtain by direct measurements, however the (^{3}He/^{4}He) ratio has been measured in many different sites (i.e., planets, solar wind, meteorites) and this provides indirect determinations of the ^{3}He abundance at the solar surface. The comparison of the measurements on the Moon during the Apollo 1969-1972 missions and in the solar wind has lead Geiss (1971) to suggest a possible enrichment of the present wind with respect to meteorites. The recent reanalysis of the observational data by Bochsler et al. (1989) confirms that the zero-age main sequence abundance of ^{3}He might have been slightly lower (by about 15%) than the present day value. It is worth noticing that the solar abundance of ^{3}He itself does not give much indication on the internal structure of the Sun because it is subject to large observational uncertainties. However the ^{3}He abundance puts strong constraints on the mechanisms that can be invoked to explain the lithium depletion at the surface of the Sun. Whatever the chosen mechanism is (for instance any kind of transport processes), it should not lead to an enrichment of ^{3}He at the solar surface greater than about 15%. This puts severe constraints on the so-called non standard solar models.

3. The different theoretical interpretations

Let us review the various scenarios proposed to account for the observed Li-depletion in stars of masses $0.8M_\odot$ to $1.2M_\odot$, close to the main sequence.

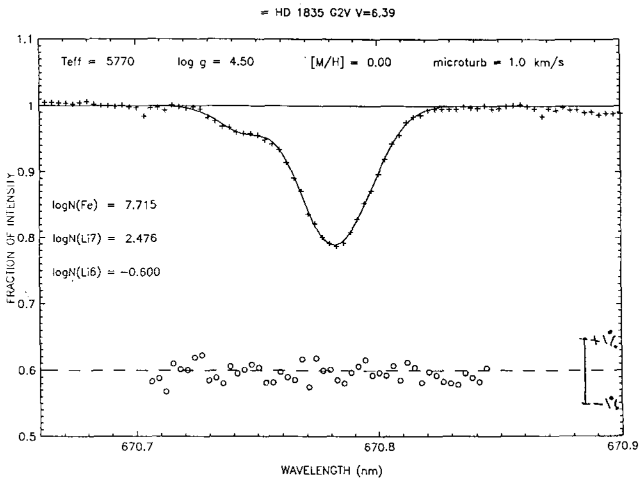

Figure 3 : ^{6}Li/^{7}Li ratio in a G2V star from Cayrel et al. (1989). The best fit of the ^{6}Li, ^{7}LI, Fe blended line at 6707 Å is obtained from a very low value of the ^{6}Li abundance.

3.1. PRE-MAIN SEQUENCE DEPLETION

Bodenheimer (1965) has suggested that the lithium depletion occurs during the pre-main sequence phase and that an abrupt drop of the lithium abundance is observed in low-mass stars (i.e., with B-V> 0.6) because, during the pre-main sequence, their convective zones reach regions sufficiently hot for Li to burn. Bodenheimer (1965) used the available modelization and obtained an acceptable fit to the observations. More recently, D'Antona and Mazzitelli (1984) showed that, with updated models, the convective zones are too shallow and that the fully mixed region has to be extended by an amount of overshooting of 0.7H_p (H_p being the pressure scale height) to get reasonable agreement with the new observations. However, the decrease of lithium abundance with stellar age as seen in a large fraction of the stars strongly suggests that only a small fraction of the depletion occurred during the pre-main-sequence stage. In any case, and even if some depletion takes place during the pre-main sequence phase, one will not be able to explain the whole set of observations without invoking a process of depletion taking place during the main sequence stage. However, this interpretationn is probably valid for Li^{6}, which burns at lower temperature.

3.2. MAIN SEQUENCE DEPLETION.

During the main sequence phase, lithium will be destroyed in stars which have convective zones extending down to the Li-burning region. From the very high temperature sensitivity of the lithium destruction rate, one would expect a very sharp drop of the lithium abundance at the spectral type where the convection zone is just deep enough to reach the Li burning region. There is no evidence for such a sharp decrease in the observations which predict, on the contrary, a very smooth dependence of the Li depletion with mass.

Weymann and Sears (1965) have first studied the effects on the solar lithium depletion of mixing by convective overshoot beneath the convective zone. Straus et al. (1976) and Cayrel et al. (1984) have shown that an agreement with the observations in clusters could be obtained only if the overshooting distance adopted depends on the mass of the star, rather than being simply equal to an arbitrary fraction of the pressure scale height. It is very difficult to accept such an ad-hoc dependence of a physical process with stellar parameters, thus it is reasonable to consider that overshooting alone is not responsible for the observed lithium depletion in stars (although it should be taken into account in the modelization).

A slow and smooth link between the nuclear destruction region and the outer convective zone is then required to account for the observations. This immediatly calls for a diffusion process acting in the radiatively stable zone, as originally proposed by Schatzman (1969). In the process of turbulent diffusion mixing the concentrations of the passive elements at the surface of the stars will then be determined by 1) the structure of the radiative zone, 2) the depth of the convective zone taking into account a reasonable extension due to overshooting processes, 3) the efficiency of the diffusion process characterized by a diffusion coefficient D.

4. Turbulent diffusion mixing during the main sequence

With the assumption that the diffusion timescale is much shorter than the evolution one, the description relies on an underlying model of the star, and on a diffusion equation for the passive contaminants, which does not influence the model itself.

4.1. THE MATHEMATICAL PROBLEM

The concentration of lithium, c, satisfies an equation of conservation of matter

$$\frac{1}{r^2}\frac{\partial}{\partial r}\rho r^2 D\frac{\partial c}{\partial r} = \rho\frac{\partial c}{\partial t} + \rho K(\rho, t)\, c$$

The diffusion coefficient, D, may be a function of radius, r, temperature, T, density, ρ and age t.

The boundary conditions are important.

At $r=r_m$ one has to insure continuity of concentration and flux

$$4\Pi r_m^2 D\rho_m\left(\frac{\partial c}{\partial r}\right)_m = \left(\frac{\partial c}{\partial t}\right)_m\int_{r_m}^{R} 4\Pi r^2\rho\, dr + c_m\int_{r_m}^{R} 4\Pi r^2 K\rho\, dr$$

The lower boundary condition is somewhat arbitrary. The roughest one would be c=o, but one can use an asymptotic value of the derivative obtained through a BKW approximation:

$$\left(\frac{\partial c}{\partial r}\right) = \left(\frac{\partial c}{\partial r}\right)_{\text{asymptotic}}$$

4.2. ESTIMATES OF THE DIFFUSION COEFFICIENT

If we assume the diffusion coefficient to be constant the diffusion equation can be written in its simplest form:

$$D\frac{\partial^2 c}{\partial r^2} = \frac{\partial c}{\partial t}$$

with a time variation of the concentration of the form $c = c_o\exp(-\lambda t)$ one gets:

$$\lambda \approx \frac{D}{h^2} \quad \text{and} \quad D \approx \frac{h^2}{T}\ln\left(\frac{c}{c_0}\right)$$

where T is the duration of the diffusion process and h is the size of the region where the diffusion acts.

In the case of the Sun this simple approximation gives:
$<D> = 1000\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for lithium, with $h= 6\ 10^{4}$ km and $c/c_0 = 10^{-2.2}$
$<D> = 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for beryllium, with $h= 10^{5}$ km and $c/c_0 = 0.3$
$<D> < 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for helium-3, with $h= 3.\ 10^{5}$ km.

This seems to indicate that the diffusion coefficient in the present Sun decreases with depth, as already stressed by Schatzman (1981).

The values so obtained for the turbulent diffusion coefficient are intermediate between the high diffusion coefficient of the convective zones ($D = 10^{13}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) and the small unavoidable microscopic diffusion ($D = 1$ to $10\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$). These values can also be compared to the estimated values required to carry angular momentum and to maintain the almost solid rotation of the Sun between 0.3 and 0.7 $R_\odot$: $D = 8000\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

4.3. MODELIZATION

4.3.1. *parameters.*

Unfortunately many parameters influence the predictions of the time evolution of the surface abundances in a stellar model:

-1) *the input physics* (essentially opacities and nuclear reaction rates) determines the global structure of the model and its evolution, which in turn states the mixing-length value (through the calibration of a solar model);

-2) *the hydrodynamical description of the transport processes*: overshooting, meridional circulation and the various hydrodynamical instabilities (see this Colloqium);

-3) *the macroscopic parameters* of the observed stars. Whereas the effective temperature is now determined with a precision of about 50°K in solar-like stars, luminosities and masses are still badly known. Higher quality data will have to wait for the results of the Hipparcos mission. A 10% variation in the luminosity would lead to a factor 10 fdifference in the predicted Lithium abundance in a solar model.

4.3.2. *the Hyades.*

The well-settled one parameter sequence of the lithium abundance in the Hyades has focused the attention of most of the theoreticians as a challenge. Any theoretical modelization should be able to reproduce the observed slope of the Li-depletion with temperature in the Hyades.

The large sensitivity of the results to the many unknown parameters which enter the modelization explains the long history of apparent successes and failures, parallel to the improvement of our knowledge concerning the physics entering the structure and the hydrodynamical processes.

Baglin et al. (1983) and Cayrel (1983) obtained the correct trend of the Hyades sequence with models including turbulent diffusion but using different numerical procedures. Baglin et al. (1985) have tested the effects on the lithium depletion of different expressions of the turbulent diffusion coefficient. They showed that 1) a diffusion coefficient of the form $D= Re^*\nu$ where ν is the microscopic viscosity and Re^* a pseudo-Reynolds number cannot explain the observed slope because the microscopic viscosity varies too abruptly with effective temperature; 2) the observations were explainable with a diffusion coefficient of the type $D= \alpha(\nabla_{ad}-\nabla_{rad})^{-1}$ which has a sharp decrease just below the convective zone but almost remains constant in a large part of the diffusion region.

However a revision of the input physics (inclusion of low-temperature opacities, updating of the nuclear reaction rates) leads to standard solar models with higher mixing-length values (Lebreton and Maeder, 1986) and with a somewhat different structure of the outer layers. Baglin et al. (1987) have reconsidered the problem using this new input and taking into account the uncertainties in the observed parameters. They conclude that the high and low-mass stars models are difficult to reconcile: convective zones look too small, an important amount of overshooting is needed to extend them and an almost constant diffusion coefficient is required. In particular, the turbulent diffusion coefficient derived by Zahn (1983),

$$D = \frac{4}{5}\frac{r^6}{G^2}\Omega^2\frac{L^2}{M^3}\frac{1}{\left(\nabla_{rad} - \nabla_{ad}\right)}\left(1 - \frac{\Omega^2}{2\Pi G\rho}\right) \qquad (1)$$

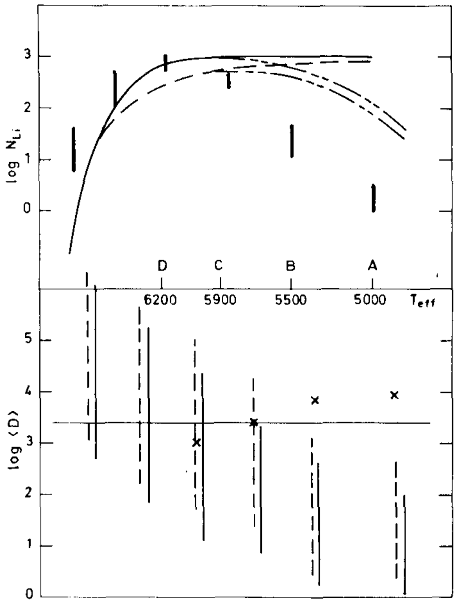

Figure 4a : Predicted surface lithium abundance in the Hyades using a diffusion coefficient given by (1) for the two extreme values of the rotational velocities (continuous line and dashed line correspond respectively to the minimum and maximum value of the observed rotational velocity). The observed values (thick lines) are given for comparison. The effect of an overshooting region expanding over 0.7 H_p is shown (double dashed lines).

Figure 4b : The diffusion coefficient as given by (1) in the diffusion region of the corresponding models in the two hypothesis for rotation, compare to the "effective diffusion coefficient" (crosses) needed to obtain the observed values of the lithium abundance.

which relates the degree of mild turbulence to the rate of differential rotation, decrases very rapidly with the mass in low-mass stars (see fig. 4 where D has been calculated with the most recent determinations of the rotational velocities in the Hyades). According to Baglin and Morel (1989) this coefficient is unable to reproduce the observed slope of the lithium depletion in the cooler Hyades stars although for higher temperatures Vauclair (1988) uses this expression to interpret the lithium dip around T_{eff}= 6700°K discovered by Boesgaard and Tripicco (1986a). It appears then that if (1) were a good candidate for the diffusion coefficient, it should be complemented by an additional mechanism sensitive to the mass, which would be able to decrease the efficiency of the depletion during the main sequence phase.

4.3.3. *lithium abundance in the sun and older clusters.*

To be significant, the comparison of the surface lithium abundance in the Sun and in the Hyades has to be made with a one solar mass star and not at the same T_{eff}, as the evolution from the Hyades age to the solar one corresponds to an increase of T_{eff}. A one solar mass star in the Hyades has a depletion factor of at least 1.5; this would lead to a deficiency of the order of 10^{-3} at the age of the Sun, if the depletion was continuously acting at the same rate. This means that the predicted depletion is too large between 8. 10^8 and 4.5 10^9 years., i.e., that the diffusion coefficient has decreased. As during this phase the star spins down, the velocity field and the turbulence generated by the motions induced by rotation have also probably decreased. These facts are then consistent with a scenario of the kind proposed by Zahn (1987), and suggests to withdraw the assumption of a time independent diffusion coefficient.

The time dependence of the angular velocity is linked to the complex process of spin-down and angular momentum loss, as discussed in this colloquium. In the absence of a precise modelization, only crude estimates are possible. In a first approach Schatzman (1989) suggests a time dependence of the form, $\Omega = \Omega_0(1 + t/t_0)^{-3/4}$, t_0 being the time elapsed between the end of the spin-up and the arrival on the main sequence, and Ω_0 the initial angular velocity. If the diffusion coefficient is assumed to be given by (1) its time dependence can then be written in the following form: $D(t) = D_0 (1 + t/t_0)^{-3/2}$.

With the assumption that the variations of the underlying model are negligible only the timescale is changed. As t increases D(t) becomes very small and the abundance tends to a finite limit. If around one solar mass t_0 is of the order of 3 10^8 years (Schatzman, 1989), then the process is already important for a cluster like the Hyades, and dominates at solar age. The depletion is then $\log (c/c_0)_\odot = 1.5 \log(c/c_0)_{\rm Hyades}$. This factor is of the right order of magnitude comparing the sequences of the Hyades and of M67. In addition this process might also help solving the difficulty stressed in § 4.3.2. as it introduces an additional mass dependence of Ω through the characteristic time t_0.

4.4 CONSISTENT MODELIZATIONS

As already said, a complete modelization has to take into account the effects of the evolution of the model. The numerical problem becomes then more complicated and the results are less easy to understand and to handle as no algebric dependence exists.

4.4.1. *Helium-3 abundance in the Sun*

For elements like lithium, which do not influence the nuclear evolution, the hypothesis of constancy of the model is reasonable. When studying helium, the model has to be relaxed and one has to solve at the same time the diffusion equation and the equation of evolution.

Lebreton and Maeder (1987) have calculated non-standard models involving mild turbulent diffusion mixing. The turbulent diffusion coefficient chosen is $D = (8r/H_p)\nu$ where ν is the microscopic viscosity. This expression was grossly derived from Zahn's (1983) estimate and is in good agreement with the observational constraints on D. The results show that with this coefficient, diffusion has to be reinforced by a moderate amount of overshooting ($0.6H_p$) in order to be able to give at solar age the observed depletion of lithium at the surface of the Sun. Furthermore the efficiency of mixing in the region associated to the ^{3}He peak is quite moderate and these models lead to a secular enrichment of ^{3}He in the solar atmosphere compatible with the observational limit given by Bochsler et al. (1989).

4.4.2. *The consistent modelization of Pinsonneault et al.*

The most consistent approach at the moment is presented by Pinsonneault et al. (1989). An evolutionary sequence, of a rotating star is followed from the wholly convective phase, including the transport of both angular momentum and chemicals. Diffusion coefficients are estimated from several instabilities and an ad-hoc scaling factor reduces the diffusion coefficient of chemicals with respect to the angular momentum one. Many parameters enter this model. Some of them can be fixed by the available observational constraints : the angular velocity of the Sun at the solar age and the lithium abundance as a function of age. The observed range of Li abundance in cluster stars of similar masses is interpreted as a consequence of a spread in the initial angular momentum.

5. Conclusions

The available observational data have not yet been explained in a completely consistent way. Although it seems reasonable to associate transport processes with the instabilities related to rotation, the physical mechanism is not yet understood. Many parameters enter the stage, and are difficult to include in the simulations: evolution of the star, spin-down, different hydrodynamical instabilities... But, at the moment we know the angular velocity distribution only in the case of the Sun at the solar age and the surface abundances for some other stars, whereas generally mass is unknown and luminosity is very unprecise.

With future space projects like the astrometric satellite HIPPARCOS and the stellar seismology experiment EVRIS we will have considerably more data relevant to this problem. Progress is also needed on the theoretical side to firmly establish the hydrodynamical state of a rotating star.

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